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Dense molecular gas in quasar host galaxies: a search for HCN emission from BR B1202−0725 at $z = 4.695$

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ABSTRACT

We report on the results of a search using the VLA for redshifted HCN(1–0) emission from the host galaxy of BR B1202−0725, an optically luminous quasar at $z = 4.695$. The host galaxy emits strongly in the rest-frame far-infrared, and shows characteristics very similar to those of more local ultraluminous infrared galaxies, in which a significant fraction of the far-infrared emission is powered by star formation. We find a 3-σ upper limit to the HCN(1–0) emission of 4.9×10^{10} K km s^{-1} pc^2, assuming a Λ-cosmology. This limit is consistent with correlations derived from measurements of HCN, CO, and far-infrared emission for a sample of more local galaxies including starbursts (Solomon et al. 1992a).

Key words: Galaxies: evolution, galaxies: starburst; quasars: general, quasars: individual: BR B1202−0725, radio lines: galaxies

1 INTRODUCTION

Establishing the role of star formation in the early universe is key to understanding the formation and evolution of galaxies. Early searches for the fingerprints of star formation at high-redshift received a tremendous boost with the identification of the IRAS source F10214+4724 as a hyperluminous infrared galaxy at $z = 2.286$. Millimetre and submillimetre observations pointed to the presence of $\sim 10^8$ M$_\odot$ of dust (Clements et al. 1992), and a molecular gas mass of $\sim 10^{10}$ (Solomon, Downes & Radford 1992b). Subsequent observations and analysis showed that 10214+4724 was gravitationally lensed (e.g., Downes, Solomon & Radford 1995). Nonetheless, F10214+4724 remains a ultraluminous infrared galaxy (ULIRG), most likely undergoing one of its first massive bursts of star formation.

ULIRGs represent a remarkable class of object, emitting a significant fraction of their considerable bolometric luminosity at infrared wavelengths. With $L_{\rm FIR} > 10^{12}$ L$_\odot$ there is increasing evidence to suggest that a large fraction of ULIRGs have recently been in, or are currently undergoing, some sort of merger or galaxy-galaxy interaction (e.g., Sanders & Mirabel 1996). These tidal interactions are believed to trigger both extreme bursts of star formation and the turn-on of a central active galactic nucleus (AGN), both of which are observed, often simultaneously, in ULIRGs. Local ULIRGs have been studied extensively at millimetre/submillimetre wavelengths to assess the relative importance of star formation, primarily through measurements of the molecular gas (e.g., Solomon, Downes & Radford 1992a; Solomon et al. 1997; Gao 1996). Important results have come from these studies: in spite of the extreme CO luminosities observed in ULIRGs, the ratio of $L_{\rm FIR}/L_{\rm CO}$ is an order of magnitude larger than normal spiral galaxies; also, measurements of the dense gas tracer HCN(1–0) show that a considerable fraction of the molecular gas in ULIRGs has densities commonly observed in star forming cores. These two results can be interpreted as high star formation rate per unit molecular gas mass, and a high star formation potential. The discovery of ULIRGs at early epochs thus raises the question of whether star formation in high-redshift sources is similar to that seen in local analogues?

The current generation of millimetre/submillimetre cameras (MAMBO and SCUBA operating at the IRAM-30m and the James Clerk Maxwell Telescopes respectively) has identified many candidate high-redshift ULIRGs, both through targeted observations of objects known to be at high-redshift (e.g., Archibald et al. 2001; Carilli et al. 2001) and through blank-sky surveys (e.g., Bertoldi et al. 2000; Hughes et al. 1998). Optical studies have shown that low-redshift quasars are located in massive host galaxies (e.g., Boyce et al. 1998; Pagani, Falomo & Treves 2003). By extension, high-redshift quasars provide a convenient means by which to pinpoint very distant, massive galaxies. Many high-redshift quasar host galaxies have been detected in the (sub)mm continuum (e.g., McMahon et al. 1994; Barvainis & Ivison 2002; Omont et al. 2003; Bertoldi et al. 2003), indicating the presence of massive quantities of dust 10^{8-9} M$_\odot$ at early epochs. The interpretation of the (sub)mm continuum observations is not without complications, however, since the underlying source of the UV energy heating the dust can be due to either AGN and/or starburst activity. CO emission has also been detected from a number of these sources (e.g., Ohta et al. 1996; Omont et al. 1996; Carilli et al. 2002a), unveiling

massive molecular gas reservoirs of 10^{10-11} $M_\odot$, and providing supporting evidence for massive starbursts at less than 10% of the age of the Universe.

One of the most spectacular examples of this class of object is BR B1202−0725, the most distant ($z = 4.695$) and optically luminous ($M_B = -28.5$) radio-quiet quasar of the BR(I) quasars (Storrie-Lombardi et al. 1996). The first $z > 4$ quasar to be detected at (sub)mm wavelengths (McMahon et al. 1994; Isaak et al. 1994), BR B1202−0725 was found to contain $\sim 10^9$ $M_\odot$ of dust at a temperature of ~ 50 K. CO observations traced more than 10^{11} $M_\odot$ of molecular gas (assuming locally-determined conversion factors). A multi-line LVG analysis by Ohta et al. (1998) using a range of CO transitions (CO(7–6): Omont et al. 1996; CO(5–4): Ohta et al. 1996; Omont et al. 1996; and CO(2–1): Ohta et al. 1998) suggested that the molecular gas density is $> 10^4$ cm^{-3}. This conclusion was also reached by Carilli et al. (2002b) using data having a much higher signal-to-noise ratio. The modelling requires a number of assumptions, and it is clear that a direct measure of the dense gas is desirable in order to establish whether the host galaxies of high redshift quasars are indeed the analogues of nearby ULIRGs.

With few exceptions, studies of the molecular interstellar medium in very distant galaxies have used the CO rotational ladder. With a critical density of $> 10^4$ cm^{-3}, the lowest of the HCN rotational line traces molecular gas at a much higher density than the corresponding CO transition. In this paper we present a search for HCN(1–0) emission from BR B1202−0725 using the Very Large Array (VLA) of the National Radio Astronomy Observatory[1], with the aim of providing an independent measure of the dense gas component in its host galaxy, and to enable a direct comparison with the local ULIRGs observed by Solomon et al. (1992a). The mean rest frequency of the HCN(1–0) triplet is $\nu_{\rm rest} = 88.632$ GHz, which is redshifted to 15.563 GHz in BR B1202−0725. All quantities given here have been derived using a Λ-cosmology, with $H_0 = 65$ km s^{-1} Mpc^{-1}. For comparison, the same quantities derived for a flat, Einstein-de Sitter cosmology with $H_0 = 50$ km s^{-1} Mpc^{-1} are included in parentheses. These cosmologies give a luminosity distance $D_{\rm L} = 46.6(39.6)$ Gpc for BR B1202−0725.

2 OBSERVATIONS AND DATA REDUCTION

The VLA observations were made on 2000 August 26, September 2–4, and in 2003 January 25–29. In 2000 the VLA was in the compact D configuration, while in 2003 it was in the DnC configuration. The instantaneous bandwidth of the VLA is only 50 MHz, tuneable in finite steps of 20 or 30 MHz. We therefore chose a set-up for the local oscillators that most closely centred the redshifted HCN(1–0) line in the 50 MHz bandwidth, and covered the 50 MHz with 8 channels of 6.25 MHz (120 km s^{-1}) with both right and left circular polarizations. The narrow total bandwidth of the current 15 GHz receivers at the VLA esulted in the sensitivity achieved the frequency of the redshifted HCN line being degraded by a factor of about 2 relative to the centre of the band. Antenna-based complex gains were monitored every 15 minutes through observations of the quasar PMN J1149−0740. The bandpass and absolute flux density scale were determined through observations of 3C273 and 3C286 respectively. The total uncertainty in the flux density calibration is estimated to be less than 5 per cent.

The tropospheric phase stability was relatively poor for the observations made during 2000 late summer, and the data with particularly bad phase coherence (typically those on the longest baselines in the D configuration) have been edited. The weather during 2003 January was excellent. The data were reduced and imaged using the Astronomical Image Processing System (AIPS). After combining the data from both sets of observations, the resulting naturally-weighted synthesized beam is 4.6×4.4 arcsec^2 at position angle -60°. The rms noise per channel in the final image is 60 μJy beam^{-1}.

3 RESULTS AND DISCUSSION

No redshifted HCN(1–0) emission is detected. The central six channels are displayed in Fig. 1, with 2-σ contours of 120 μJy beam^{-1}, and crosses denoting the positions of the two millimetre sources detected by Omont et al. (1996). The CO lines reported by Omont et al. have line widths of 190 and 350 km s^{-1}; assuming an intrinsic line width $\Delta V_{\rm line}$ for any HCN emission of ~ 250 km s^{-1} we find a 3-σ upper limit to the HCN(1–0) emission of $(3 \cdot (\Delta V_{\rm line}/\Delta V_{\rm channel})^{1/2} \cdot$ rms per channel) = 31 mJy km s^{-1}. Using equations 1 and 3 from Solomon et al. (1992b), we derive a 3-σ upper limit to the line luminosity of $L'_{\rm HCN} < 4.9(3.6) \times 10^{10}$ K km s^{-1} pc^2.

In order to compare the molecular properties of BR B1202−0725 with those of local (U)LIRGs we include it in plots of $L'_{\rm HCN}$ vs. $L_{\rm FIR}$, and $L_{\rm FIR}/L'_{\rm CO}$ vs. $L'_{\rm HCN}/L'_{\rm CO}$, in Fig. 2. The value for the far-infrared luminosity, $L_{\rm FIR} = 6.3(4.6) \times 10^{13}$ $L_\odot$, has been calculated by integrating under the thermal greybody spectral energy distribution as detailed by Isaak et al. (2002). The CO(1–0) luminosity comes from a recent measurement of the CO(1–0) line flux, $S_{\rm CO} = 0.17 \pm 0.05$ Jy km s^{-1} (C. Henkel, private communication). The upper limit of $L'_{\rm HCN}$ for BR B1202−0725 is consistent with the correlations between $L'_{\rm HCN}$ vs. $L_{\rm FIR}$, and $L_{\rm FIR}/L'_{\rm CO}$ vs. $L'_{\rm HCN}/L'_{\rm CO}$, observed in more local (U)LIRGs.

Our measured upper limit suggests that the globally-averaged molecular properties of the host galaxy of BR B1202−0725 are consistent with those found in more local ULIRGs. Furthermore, it is consistent with the interpretation that a large fraction of the far-infrared luminosity originates from dust heated by star formation. We note, however, that a significant fraction of ULIRGs show signs of both starburst and AGN activity (Genzel et al. 1998). This has also been found to be the case in many of the high-redshift sources identified in submillimetre surveys that have exploited the lensing effect of galaxy clusters (e.g., Smail, Ivison & Blain 1997). It is therefore not surprising that a naked AGN residing in a young host galaxy might show similarities with ULIRGs.

A deeper limit to the HCN emission from BR B1202−0725 will only be possible with the EVLA[2], when an improvement in sensitivity of a factor of about 6 is anticipated for spectral line work at this frequency. With our current limit we do, however, exclude a low $L_{\rm FIR}/L_{\rm HCN}$ ratio. Such a ratio would be interpreted as a host galaxy with a high molecular gas density with little ongoing star formation or AGN activity, that is, gas that is *about* to form stars or be accreted onto a central black hole. A high $L_{\rm FIR}/L_{\rm HCN}$ ratio is

[1] The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

[2] Details of the VLA expansion project may be found at http://www.aoc.nrao.edu/evla/

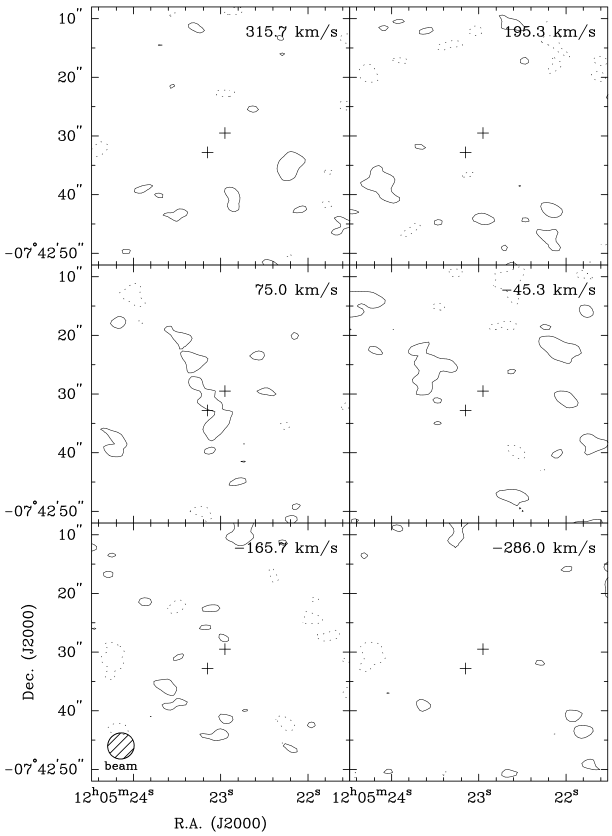

Figure 1. Channel maps of the search for redshifted HCN(1–0) emission from BR B1202−0725. Contours are at 2-σ intervals of 120 μJy beam^{-1}. The synthesized beam is given in the bottom left panel. The crosses denote the positions of the millimetre continuum sources detected by Omont et al. (1996). The velocity in the top right of each panel is relative to a redshift $z = 4.695$.

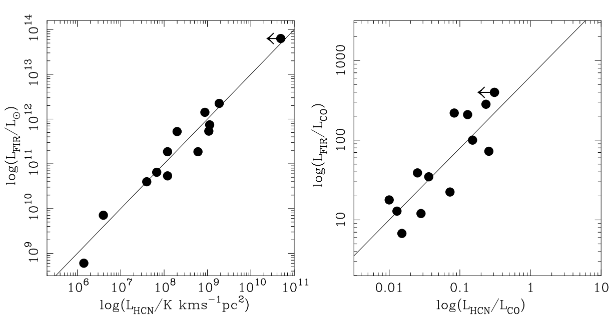

Figure 2. *Left:* $L_{\rm FIR}$ vs. $L_{\rm HCN}$ for a sample of galaxies, ranging from normal galaxies to those undergoing massive starburst, from Solomon et al. (1992a). The solid line represents a simple least-squares fit to the Solomon et al. data points. The arrow at top right represents the 3-σ upper limit to $L_{\rm HCN}$ for BR B1202−0725 reported here. *Right:* $L_{\rm FIR}$ vs. $L_{\rm HCN}$ normalised by the CO luminosity, after Solomon et al. (1992a).

still consistent with the measured upper limit, and would indicate that a significant contribution is made to $L_{\rm FIR}$ from dust heated by the central AGN, rather than by star formation. A global measure of the HCN emission from a galaxy in which both AGN and starburst activity are observed cannot definitively establish the dominant source of the far-infrared luminosity, as strong HCN emission is seen in both starbursts and local AGN (Seyfert galaxies: Curran et al. 2001). Differentiating between the two may be possible with images of both considerably higher angular resolution and of higher HCN transitions. In this way it should be possible to trace the distribution of the denser gas as well as its excitation.

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